Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

“Electron wires” for long-range beam-beam compensation in the LHC

Giulio Stancari
Fermilab

Workshop on Simulations and Measurements of Long-Range Beam-Beam Effects in the LHC
Lyon, France, November 30, 2015

Contributors and collaborators

Y. Papaphilippou, H. Schmickler (CERN), D. Noll (IAP)
V. Shiltsev, G. Stancari, A. Valishev (Fermilab)

Many thanks to
O. Aberle, G. Arduini, A. Bertarelli, F. Bertinelli, R. Bruce, O. Brüning, R. De Maria, S. Fartoukh, M. Fitterer, W. Herr, R. Jones, G. Papotti, A. Patapenka, T. Pieloni, S. Redaelli, A. Rossi, B. Salvachua, B. Salvant, R. Steinhagen, R. Tomàs, G. Tranquille, G. Valentino, J. Wagner, F. Zimmermann (CERN), G. Apollinari (Fermilab), M. Blaskiewicz, W. Fischer, X. Gu (BNL), D. Grote (LLNL), D. Shatilov (BINP), J.-L. Vay (LBL)

HiLumi LARGE HADRON COLLIDER

LARP

Fermilab

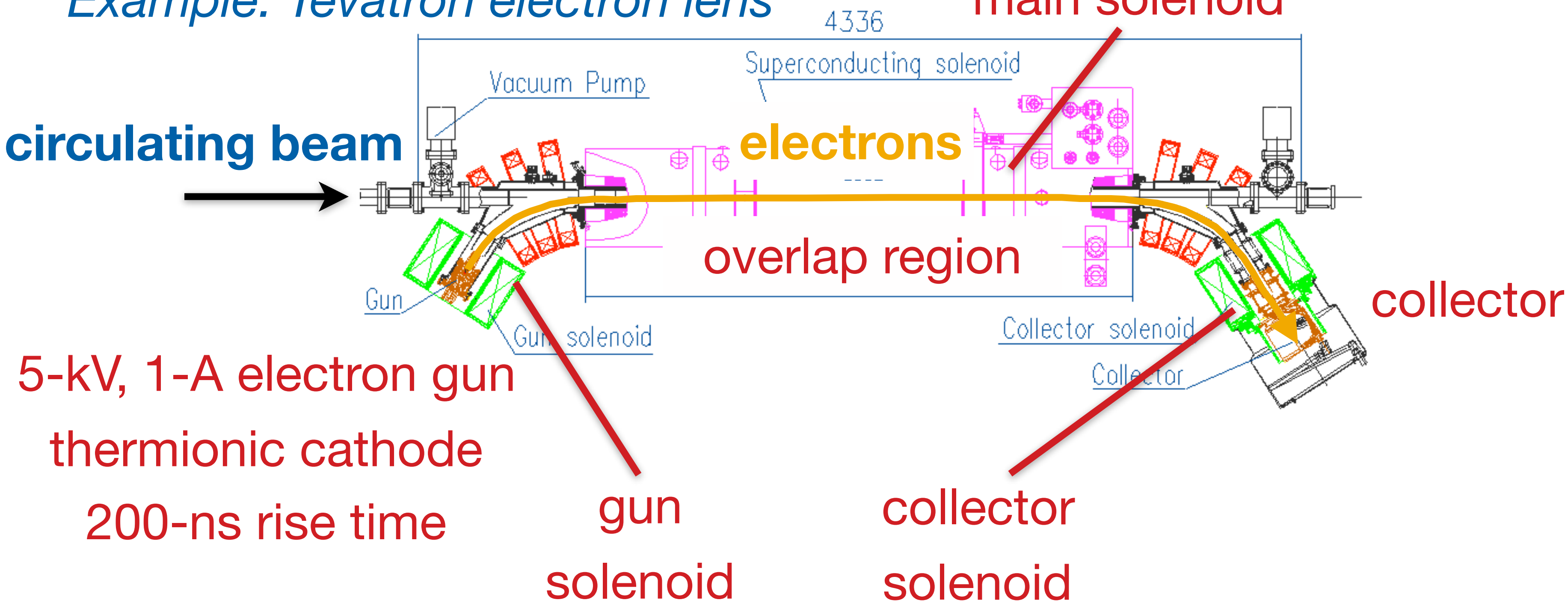
Outline

- **Introduction and motivation**
  - What's an electron lens? What can it be used for?
  - Advantages of electron lenses for long-range compensation
- **Long-range compensation with electron lenses**
  - Principles
  - Design considerations
- **Comments on beam experiments**
- **Conclusions**

What's an electron lens?

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Current-density profile shaped by cathode and electrode geometry
- Stability provided by strong axial magnetic fields

Example: Tevatron electron lens

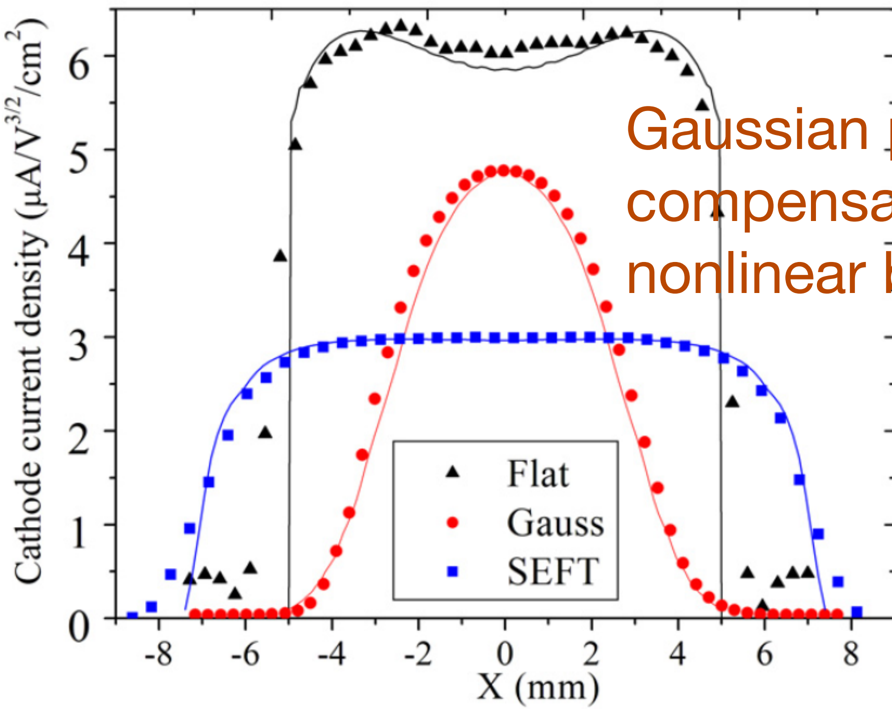


Shiltsev et al., Phys. Rev. ST Accel. Beams **11**, 103501 (2008)

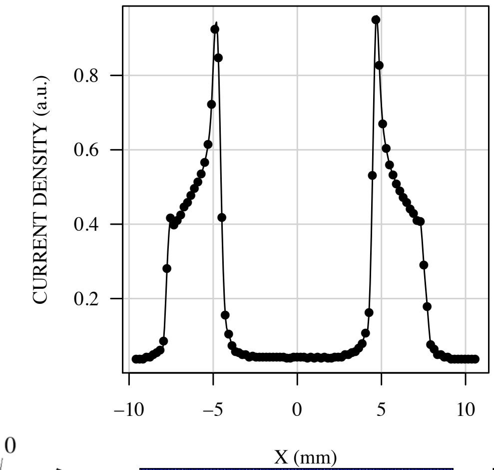
First main feature: control of electron beam profile

Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

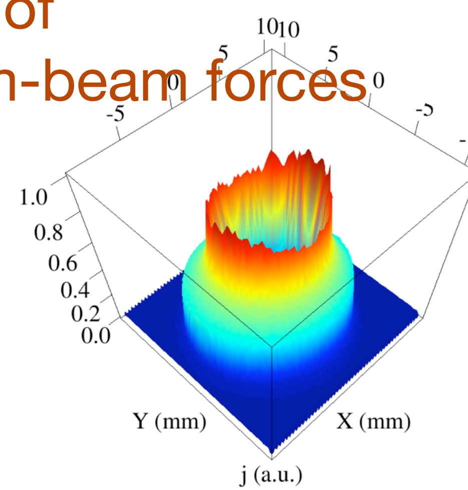
Flat profiles for bunch-by-bunch betatron tune correction

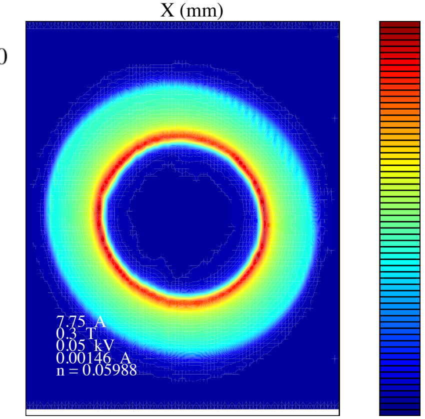


Hollow profile for halo scraping



Gaussian profile for compensation of nonlinear beam-beam forces

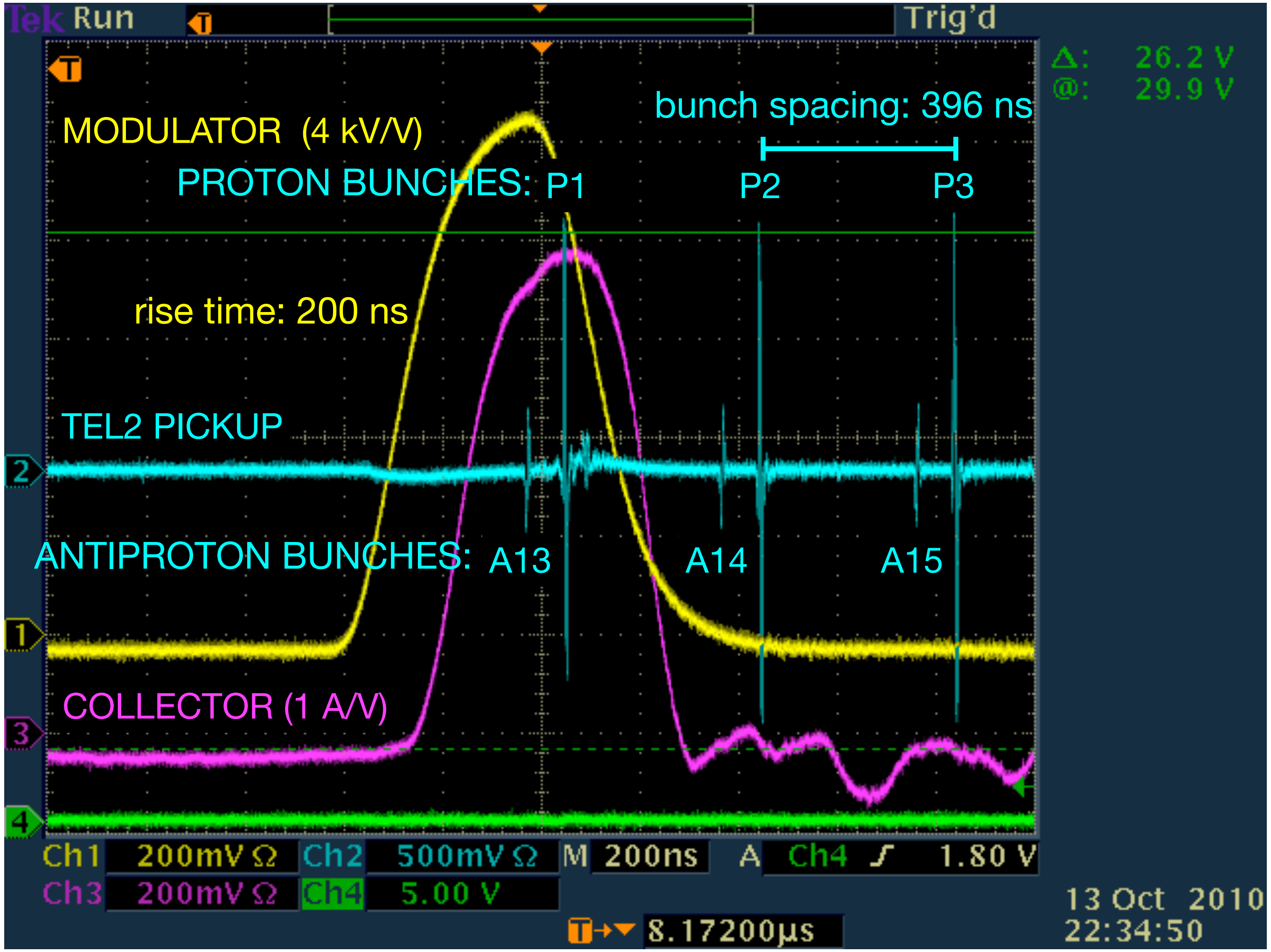




Profile is not critical for LRBBC
Profile with max. current yield (perveance) can be chosen

Second main feature: pulsed electron beam operation

Beam synchronization in the Tevatron

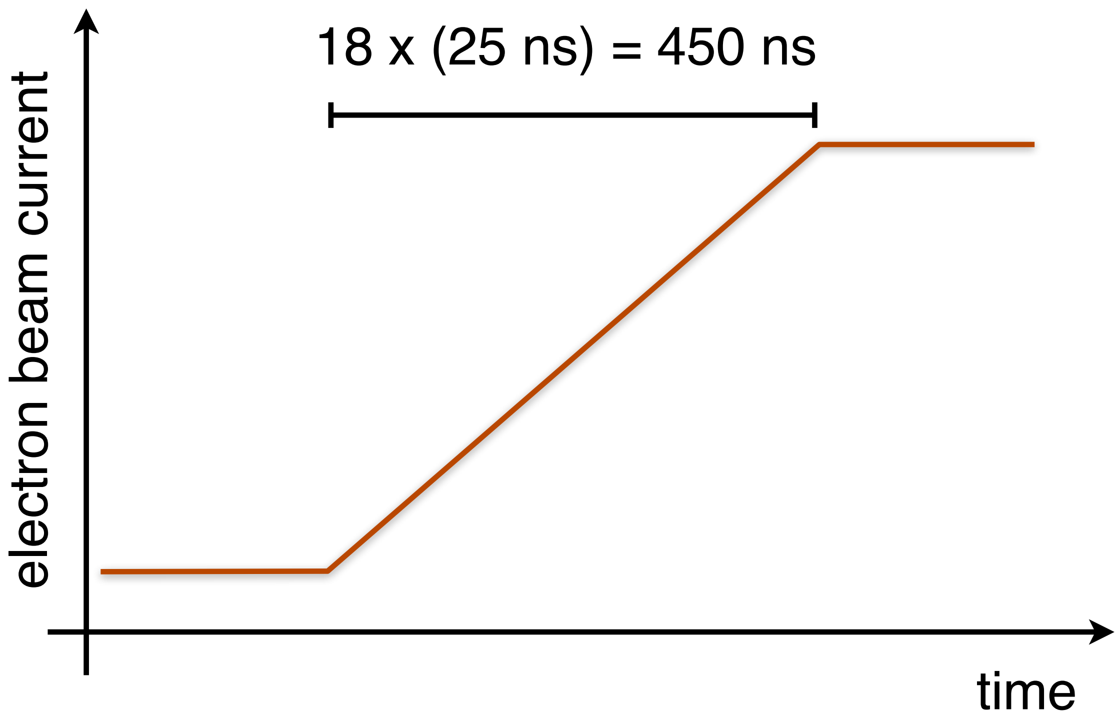


Pulsed electron beam could be **synchronized with any group of bunches**, with a different intensity for each bunch

Possibility to change compensation strength for Pacman bunches

Pulsing options for bunch tailoring of compensation strength

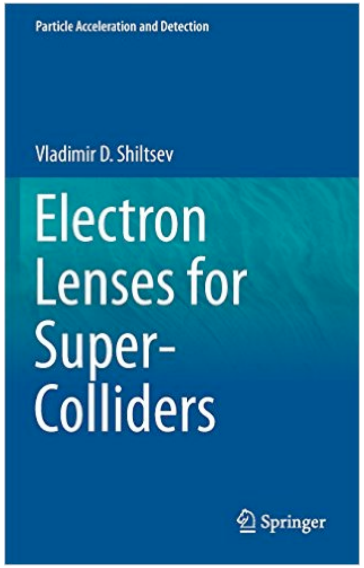
- Possible to **ramp the electron beam current** up for the Pacman bunches
- The **required repetition rate** is an important input for modulator design



Applications of electron lenses

In the Fermilab Tevatron collider

- ***long-range beam-beam compensation (tune shift of individual bunches)***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning (for years of regular operations)***
  - Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)
- ***studies of head-on beam-beam compensation***
  - Stancari and Valishev, FERMILAB-CONF-13-046-APC
- ***demonstration of halo scraping with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)

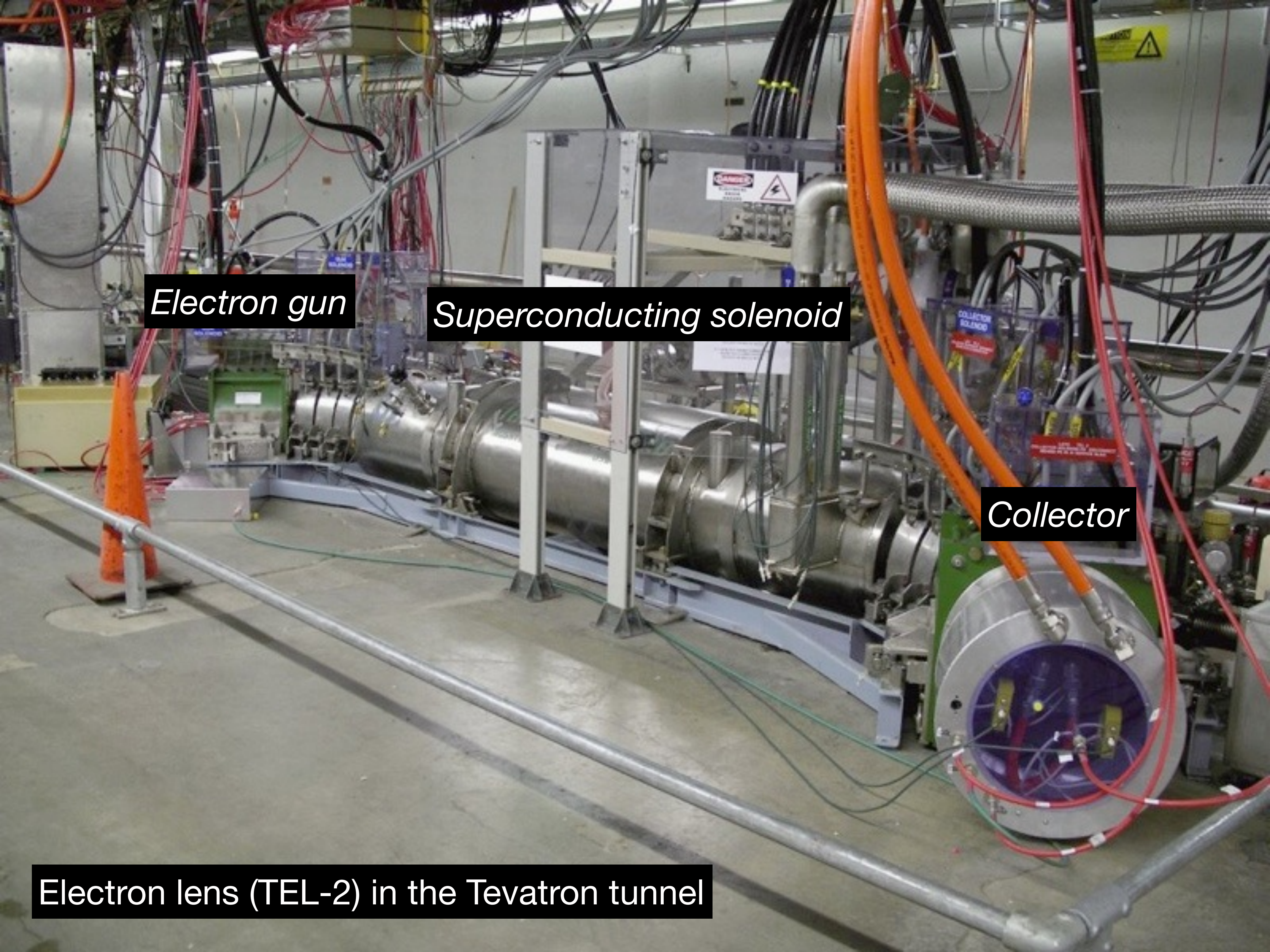


Presently, used in RHIC at BNL for head-on beam-beam compensation, luminosity improvements

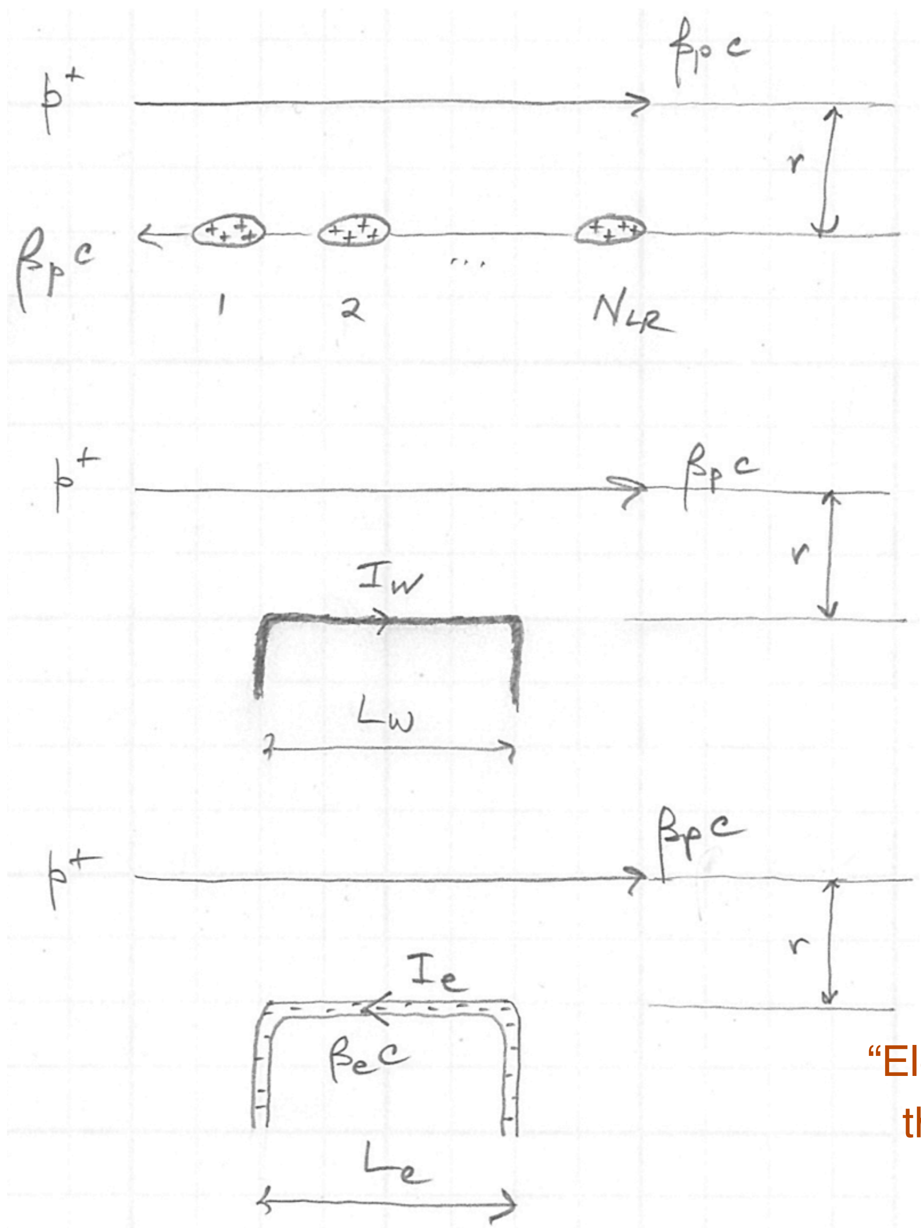
- G. Robert-Demolaize, X. Gu, IPAC15

Current areas of research

- ***generation of nonlinear integrable lattices*** in the Fermilab Integrable Optics Test Accelerator
  - Nagaitsev, Valishev et al., IPAC12; Stancari, arXiv:1409.3615, Stancari et al., IPAC15
- ***hollow electron beam scraping*** of protons in LHC
  - Stancari et al., CERN-ACC-2014-0248; Bruce et al., IPAC15
- ***long-range beam-beam compensation*** as charged, current-carrying "wires" for LHC
  - Valishev and Stancari, arXiv:1312.5006; Fartoukh et al., IPAC15
- to ***generate tune spread for Landau damping*** of instabilities before collisions in LHC


Electron gun
Superconducting solenoid
Collector
Electron lens (TEL-2) in the Tevatron tunnel

Comparison of long-range compensation schemes



momentum transfer $\Delta p_\perp$

Long-range beam-beam

$$N_{\rm LR} N_p e c \frac{1+\beta_p^2}{2\beta_p} \left(\frac{\mu_0 e}{2\pi r} \right)$$

Beam-beam kick is proportional to bunch charge *(N_p e)* and to number of interactions *N_{LR}*

Wire

$$L_w I_w \left(\frac{\mu_0 e}{2\pi r} \right)$$

Wire strength is characterized by current times length

Electron beam

$$L_e I_e \frac{1 \pm \beta_e \beta_p}{\beta_e \beta_p} \left(\frac{\mu_0 e}{2\pi r} \right)$$

"Electron wire" is charged and slow, so the effect of the current is amplified

Numerical example of ewire compensation strength

Assuming space-charge-limited emission, perveance of 5 uA/V$^{3/2}$ and L_e = 4 m

Voltage [kV]	Current [A]	Velocity β_e	Enhancement factor $(1+\beta_e)/\beta_e$	Compensation strength [A m]
2	0.45	0.088	12	22
4	1.3	0.12	9.0	46
6	2.3	0.15	7.6	70
8	3.6	0.17	6.7	96
10	5.0	0.19	6.1	123
12	6.6	0.21	5.7	150
14	8.3	0.23	5.4	178
16	10	0.24	5.1	206
18	12	0.26	4.9	235
20	14	0.27	4.7	265

← a possible operating point

Luminosity scenarios in HL-LHC

- Considering both **round** (15/15) and **flat** (10/40) **optics**
- **Luminosity leveling** with beta*
- Assuming **compensation is needed at end of leveling**, when separation decreases to ~10 sigma, a few hours into the store
  - N_p = 1.5e11
- Optimal compensation strength requirements:
  - 131 A m (round)
  - 105 A m (flat)

Layouts and geometrical constraints

- Considering **location beyond Q4**, **197.25 m from IPs**
  - (before D2, small inter-axis separation)
  - (just beyond D2, not optimal compensation)
- For Beam 1:

		Amplitude functions		Compensator position		Beam size	
Loc.	s [m]	bx [m]	by [m]	xw [mm]	yw [mm]	sx [mm]	sy [mm]
Round 15/15							
L5	6467.3	1549	751	5.8	0	0.72	0.50
R5	6861.8	752	1546	-5.8	0	0.50	0.72
L1	19796.9	1541	750	0	5.8	0.72	0.50
R1	20191.4	748	1545	0	-5.8	0.50	0.72
Flat 10/40							
L5	6467.3	584	1124	3.9	0	0.44	0.61
R5	6861.8	284	2317	-3.9	0	0.31	0.88
L1	19796.9	2314	284	0	3.9	0.88	0.31
R1	20191.4	1123	583	0	-3.9	0.61	0.44

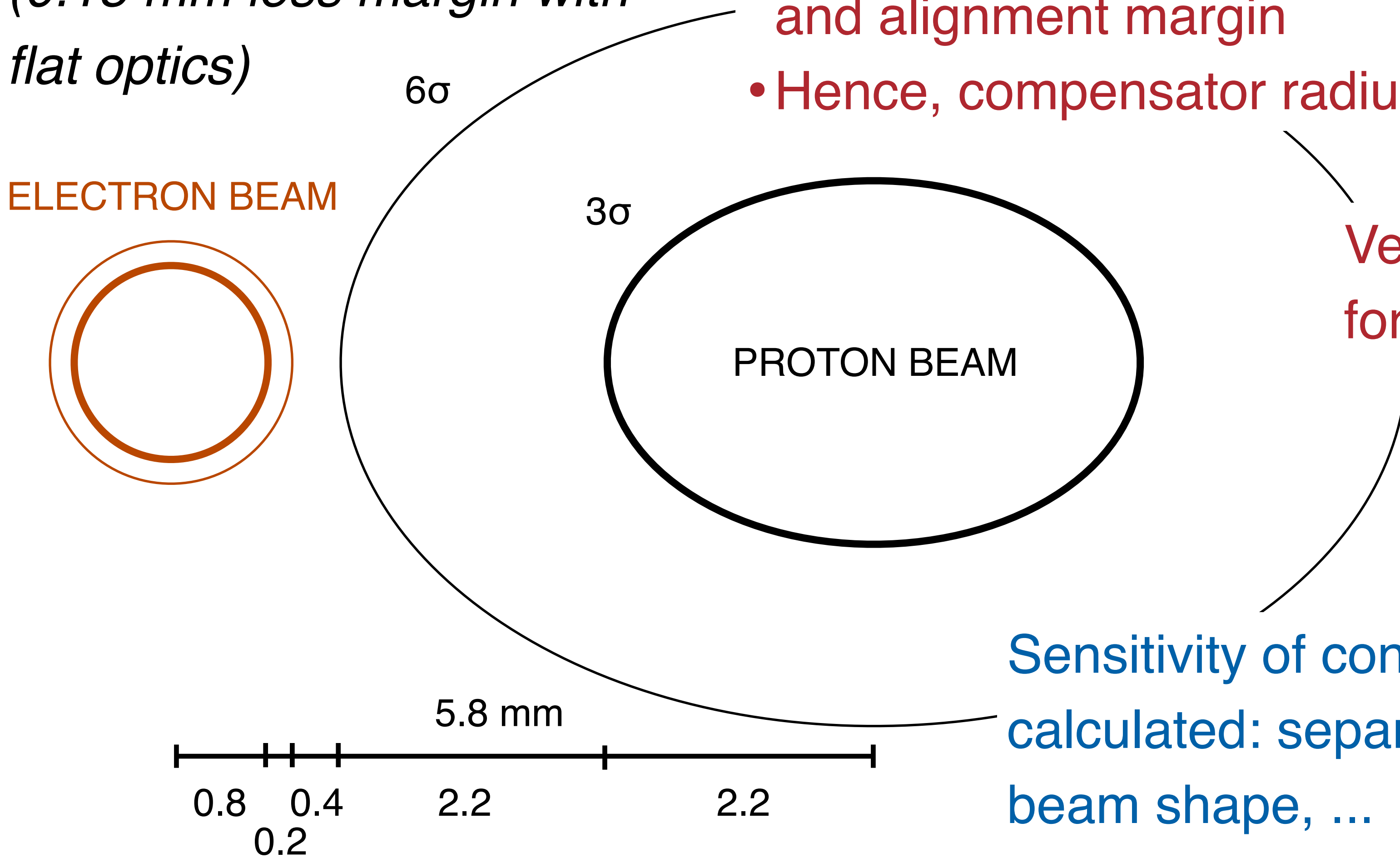
worst cases

Geometrical constraints

Beam 1, left of IP5,
round optics
(0.15 mm less margin with
flat optics)

Requirements:

- Stay clear of 6 sigma dynamic aperture
- Allow for reasonable ~0.2 mm straightness and alignment margin
- Hence, compensator radius ~0.8 mm or less



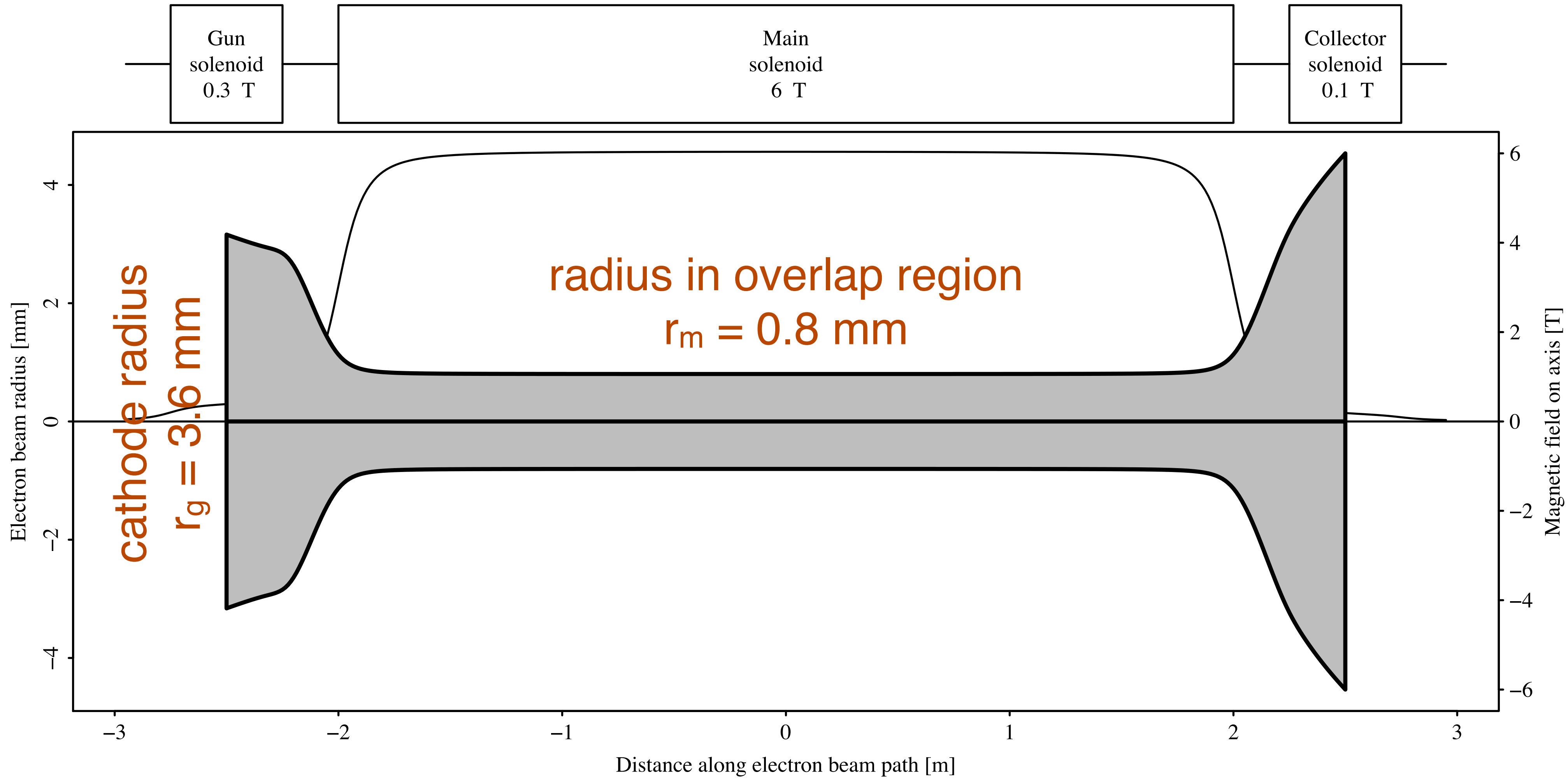
Very challenging for a metal wire

Sensitivity of configuration is being calculated: separation, wire size, beam shape, ...

Electron beam current requirements

- Need about 7 A in 2 mm^2 over 4 m
- **Can cathodes deliver enough current density?**
  - Thermionic cathodes ~ 0.2 A/mm^2
  - Scandate cathodes ~ 1 A/mm^2 (uniformity? robustness?)
  - Current density in overlap region is multiplied by compression factor of magnetic fields B_{main} / B_{gun}
    - With thermionic cathodes, need at least factor 20
    - Presently, max. is 6 T (sc technology) / 0.1 T (confinement) = 60

Example of electron beam compression

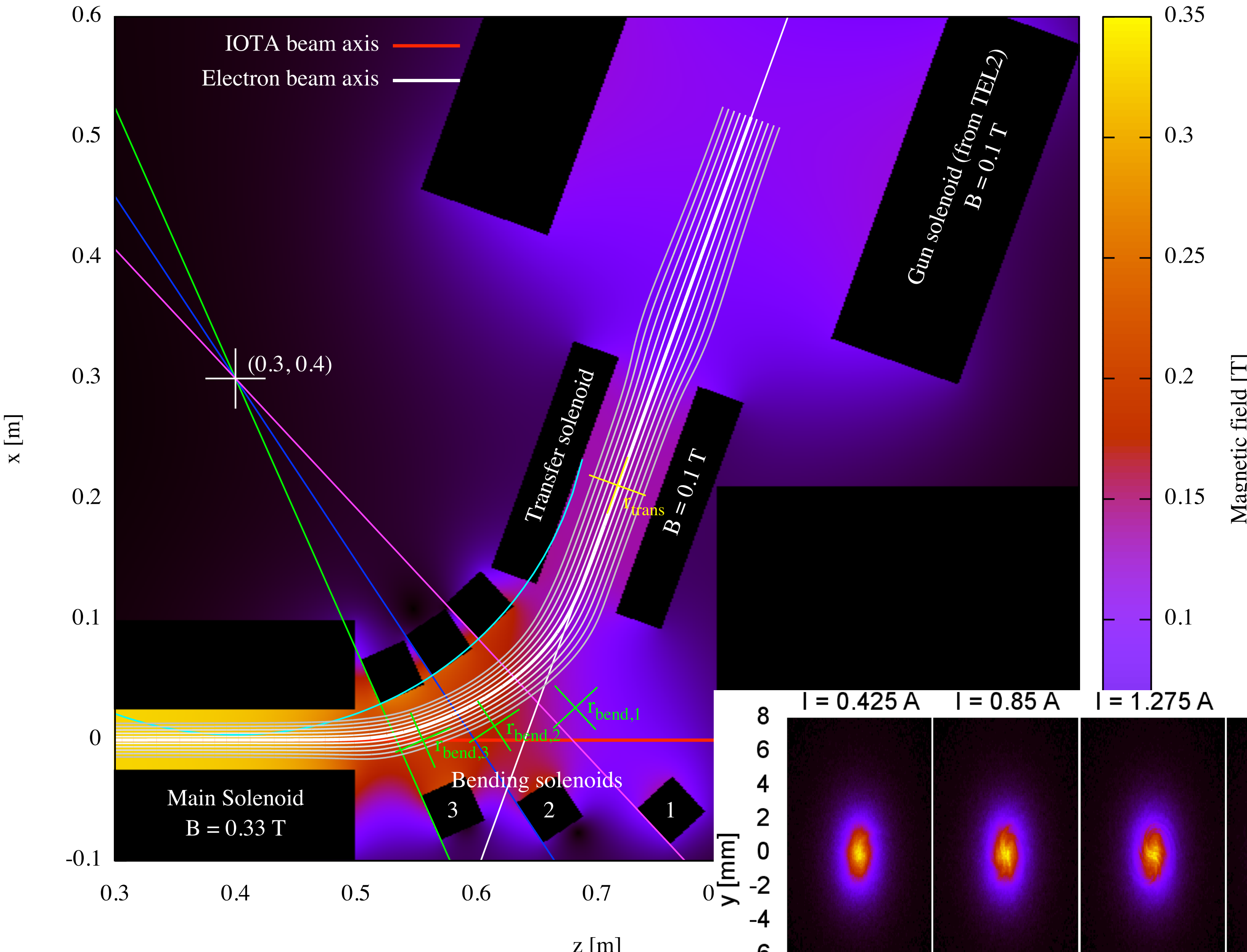


Current limits

- **Can such an intense beam be transported?**
  - Axial potential depression due to charge must not exceed kinetic energy
  - Magnetic focusing must dominate over self-field defocusing
  - There is a limit due to longitudinal fields from compression
    - analogous to beta squeeze for long bunches
    - Noll and Stancari, arXiv:1511.04507
    - analytical model and numerical simulations seem to agree
  - Desirable to keep *ExB* drift under control, but not critical for LRBBC
- May be tested experimentally with scaled experiments
- Role of chamber size

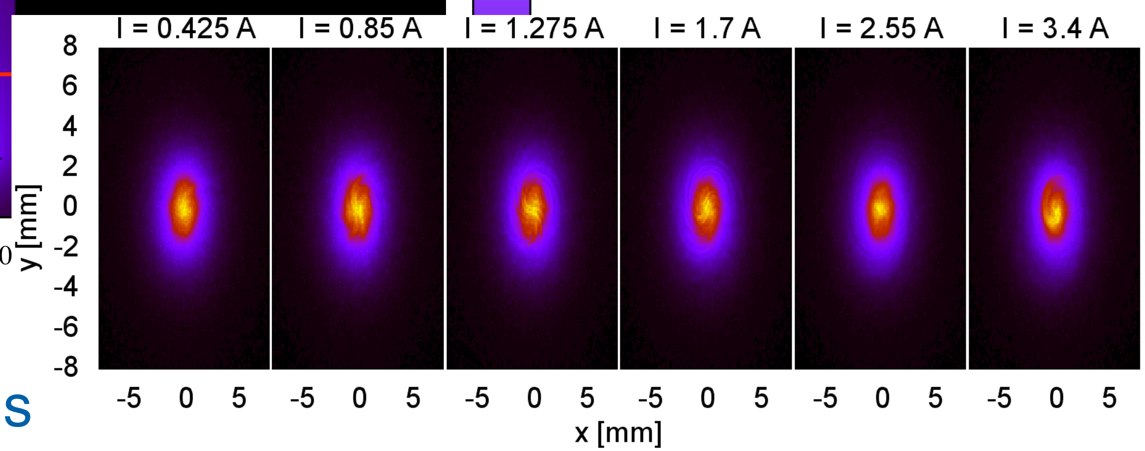
Work in progress

Design of beam transport in electron lens



1. Field-line mapping
2. Single-particle tracking
3. Tracking with space charge
4. Field maps for tracking of circulating beam

Noll and Stancari, arXiv:1511.04507



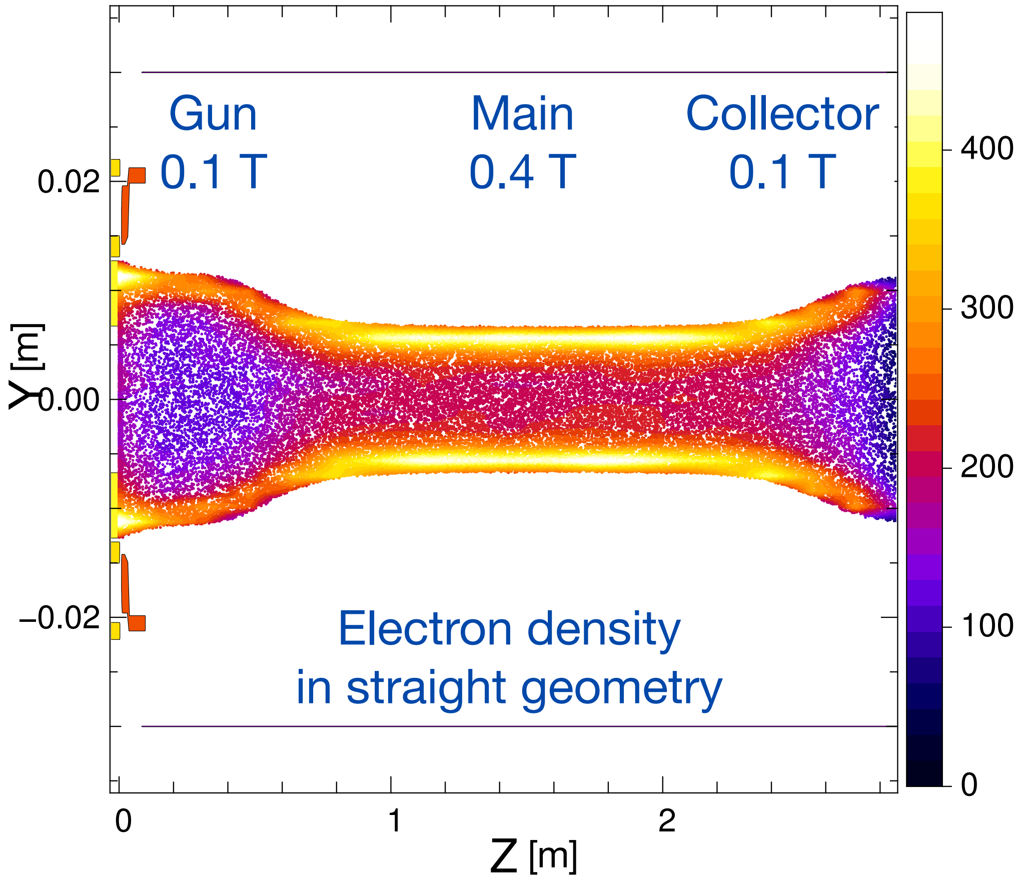
Synergy with work on IOTA e-lens

Fermilab

Dynamics of magnetically confined electron beam

3D simulation with Warp particle-in-cell code

- Basic framework was set up
- Need to
  - test injection: space-charge limited or particle distribution
  - implement toroidal sections



First use of particle-in-cell codes for electron-lens design

Moens, CERN-THESIS-2013-126
Stancari, IPAC14

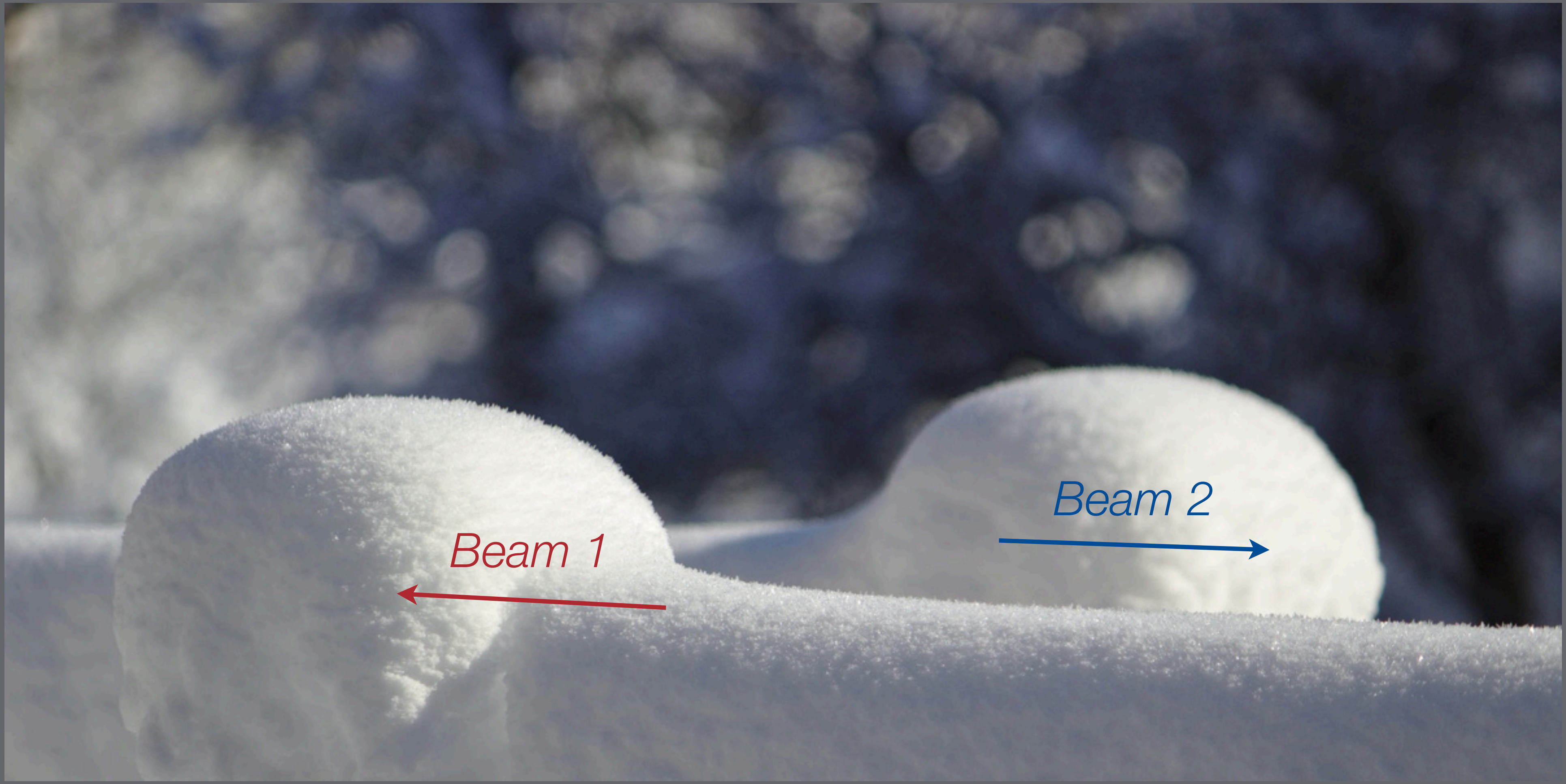
Implementation issues

- Energy dissipation: (7 A) x (12 kV) = 84 kW per device, almost DC
- Radiation damage to high-voltage modulator (must be near electron gun)
- Cost and complexity of the devices
- Reliability of hardware and reproducibility
  - TEL-1 worked in operations for 10 years for abort-gap cleaning
  - LRBBC in HL-LHC requires precise control of 8 devices
- ...

General comments on LRBBC experiments

- For any LRBBC demonstrator, **losses vs. excitation frequency** (observed recently in LHC with ADT) may give information on tune distributions, complementary to beam-transfer-function measurements. Should be exercised with known sources, such as octupoles on/off, for instance.
- For the ewire, there is experience on the interaction between circulating high-energy protons and parallel, displaced low-energy electron beams:
  - Lebrun et al., CERN-AB-Note-2004-041 (preliminary)
  - Stancari and Valishev, arXiv:1312.5006 (BB2013)
  - ...
  - We may propose dedicated experiments at RHIC
- The Fermilab electron-lens test stand can be used for scaled experiments of current limits and compression

First Snow in Chicago



Interactions

Conclusions

- Electron lenses as charged "electron wires" are a promising option for long-range beam-beam compensation in HL-LHC
  - current requirements seem achievable
  - no material close to the proton beam, safer for machine protection
  - possible pulsing for bunch tailoring of compensation strength
- Round and flat optics scenarios with luminosity leveling require similar compensation strengths
- This solution is supported by past experience and by experiments that can be planned in the near future. Of course, there is synergy with hollow electron beam collimation
- There is interest at Fermilab in participating in
  - wire demonstrator simulations and experiments
  - CERN electron-lens test stand
  - "electron wire" design
- Ideas and suggestions always welcome!

Thank you for your attention!